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DETERMINATION OF THE ADEQUACY OF HELMET VENTILATION IN A PROTOTYPE NAVY MK-12 AND THE MK-5 HARD HAT DIVING APPARATUS

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Navy Experimental Diving Unit
Washington, D. C.

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ABSTRACT

The adequacy of ventilation of a prototype Navy MK-12 diving apparatus was tested in the open circuit mode under exercise conditions of increasing severity. The tests were performed on the submerged diver at a simulated depth of 100 feet of sea water in a hyperbaric complex.

During exercise, diver's heart rate and helmet CO_2 level were measured. Analysis of the data revealed that helmet CO_2 level was linearly related to heart rate over the range of exercises performed. Further analysis gave an estimate of a maximum exercise CO_2 production of 3 liters/minute. The maximum allowable helmet CO_2 level is established as 2% and the reasons for establishing this level are discussed. The minimum helmet flow rate needed to keep the helmet CO_2 level below 2% under practically all exercise conditions was calculated to be 6 ACFM.

Comparison of the ventilatory capacity of the MK-12 with the MK-5 is also made.

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1. INTRODUCTION

A diver's ability to perform sustained work depends on several factors including physical conditioning, temperature, breathing gas density, restrictions imposed by the fit of the diving apparatus, and the helmet carbon dioxide level. Of these, the latter is probably the most important. The level of carbon dioxide in the helmet is directly proportional to the gas flow through the helmet under most conditions, thus making control of the helmet carbon dioxide level a matter of supplying adequate helmet ventilation.

Recent emphasis on reducing the noise levels in open circuit hard hat rigs have led to the quest for air supply system designs which will supply the necessary flow rates at acceptable noise levels. Since noise level seems to increase with helmet ventilation, it is important to establish adequate helmet ventilation standards so that an air supply system is not designed which sacrifices adequate helmet ventilation for a low noise level. Once a minimum adequate ventilation rate is established, it can then be used as a design criteria for air supply systems.

In the course of evaluating the new Navy Mark 12 Diving System, it became necessary to determine the adequacy of helmet ventilation under heavy exercise conditions. The MK-12 Diving System is a surface supported "Hard Hat" heavy duty tethered system designed to replace the standard U.S. Navy MK-5 "Hard Hat" system. The MK-12 consists of a lightweight fiberglass helmet, one piece dry suit, outergarment and lightweight rubber boots. The gas supply system is designed for use

either in the open circuit or close circuit recirculating mode. In the present study, the MK-12 was evaluated in the open circuit mode using air.

The purpose of the study was two fold: first, to test the adequacy of the air supply system in a prototype MK-12 in the open circuit mode and secondly, to establish a minimum acceptable helmet ventilation rate. The MK-5 diving apparatus was also evaluated to provide a basis of comparison for the MK-12.

2. METHOD

A series of five 100-foot air dives were done, 4 with the prototype MK-12 diving apparatus and one with the MK-5. In all cases, 200 feet of standard U.S. Navy diving hose was used to supply air to the divers, and overbottom pressure was measured at the upstream end of the hose to insure that the line loss was due only to the diving hose and helmet air supply system. This was felt to most closely approximate the conditions of an actual open sea diving operation.

The exercise runs were done with the diver immersed in a specially constructed fiberglass tank filled with water to a depth of six feet. The fiberglass tank was situated in the hyperbaric complex at the Navy Experimental Diving Unit. The entire complex was pressurized to a simulated depth of 100 feet of seawater. In the water, divers pedaled a bicycle ergometer at four different work rates which simulated light work to very heavy work. After an initial 5 minute rest period, the diver exercised at four 6 minute exercise periods, each exercise period

being followed by a 5-minute rest period. During the exercise runs, the divers all pedaled the ergometer at the same rate to insure that the work done in overcoming water resistance was the same in all cases. The diver's EKG was continuously monitored during exercise to obtain heart rate. Gas samples were continuously taken from two locations in the helmet, one sample from the top of the helmet, and one from just in front of the exhaust valve. The gas samples were piped through the chamber wall, expanded to one atmosphere and monitored with a Beckmen IR 315B carbon dioxide analyzer. The rate of gas sampling was approximately 300 cc/min. as measured at one atmosphere. The differential pressure between the inside and the outside of the helmet was measured continuously during all exercise runs.

Once the diver was comfortably seated on the bicycle ergometer, he was instructed to fully open his air control valve. Flow through the helmet was then regulated from the air supply manifold. A rotometer type flowmeter was used to monitor gas flow to the diver and once the flow was adjusted to the desired rate, it was kept constant throughout the dive. All measured flows were converted to ACFM. Overbottom pressure was also continuously monitored since this parameter is the one used in the fleet to regulate the divers' air supply.

3. RESULTS

Figure 1 shows the helmet CO_2 levels at the four work rates with a helmet ventilation rate of 4 ACFM. The solid line is the mean helmet

CO_2 levels for all three divers while the broken line represents one standard deviation above and below the mean.

Figure 2 shows the effect of helmet ventilation rate on the CO_2 level. The heart rate is plotted against helmet CO_2 level for the same diver on two different dives at two different helmet ventilation rates. These heart rates were taken after the diver had completed 3 minutes of a 5-minute exercise period. Since the heart rate is linearly proportional to CO_2 production, this graph is essentially a plot of helmet CO_2 level vs. relative CO_2 production. As can be seen, there is a strong linear correlation between helmet CO_2 level and heart rate. A least squares regression gives the following slopes for the two lines:

4 ACFM	Slope = 0.23
5 ACFM	Slope = 0.19

In both cases, the linear correlation coefficient was greater than .999.

Table 1 shows the overbottom pressure required to maintain the indicated flow rates to the two different diving apparatus. The pressures were measured immediately upstream of 200 feet of standard Navy diving hose with the air control valve fully open.

The valves given for the work rates in figures 1 and 2 reflect the mechanical work of pedaling the ergometer on the surface in the dry. These values do not take into account the additional work done in overcoming the impediments of the diving apparatus or the resistance of the water to body movement. Thus the actual work being done will be higher than the values given in figures 1 and 2.

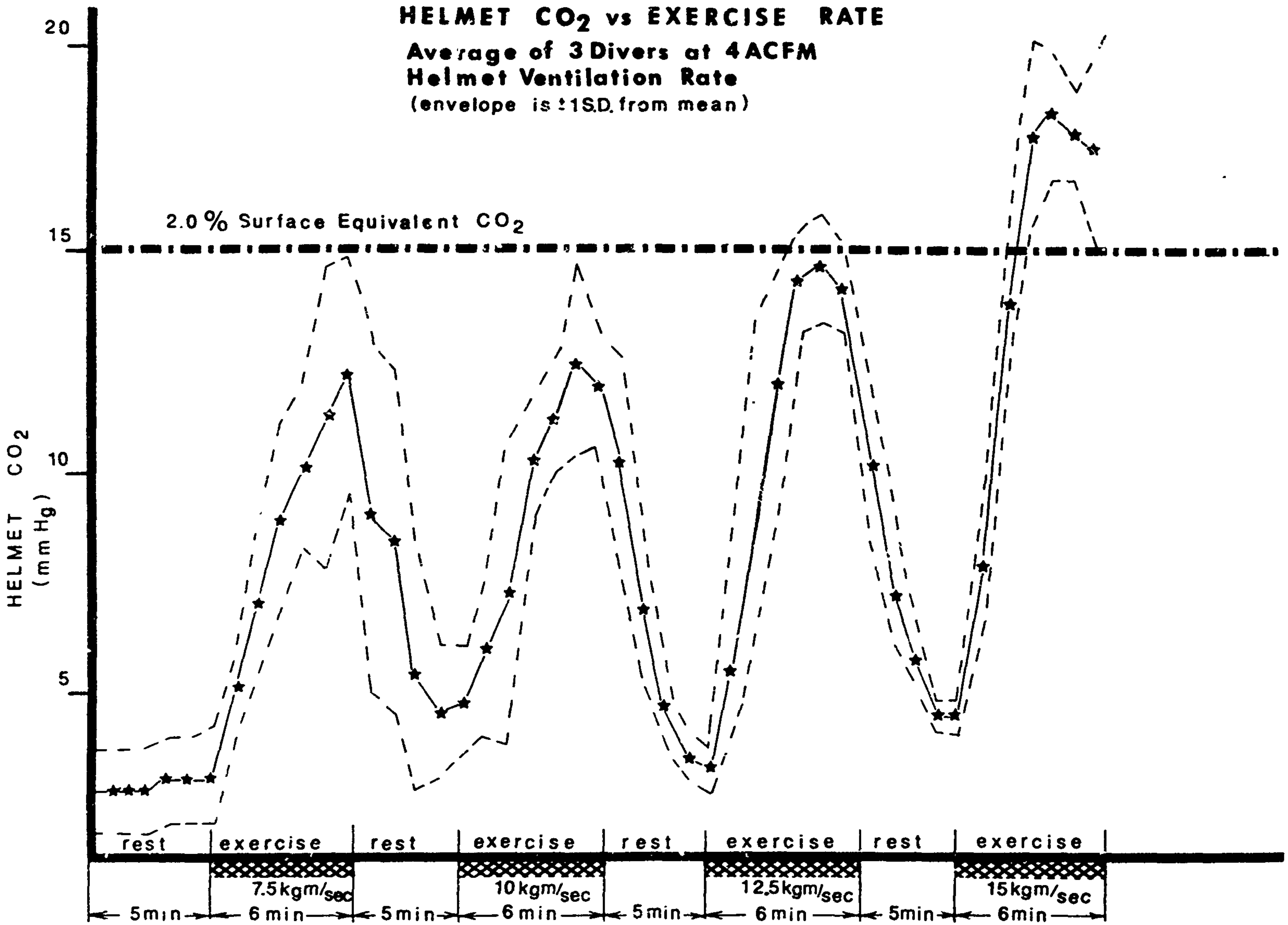
HELMET CO2 vs EXERCISE RATE
Average of 3 Divers at 4 ACFM
Helmet Ventilation Rate
(envelope is ±1S.D. from mean)
2.0 % Surface Equivalent CO2
20
15
10
5
HELMET CO2
(mm Hg)
rest
exercise
rest
exercise
rest
exercise
rest
exercise
7.5 kgm/sec
10 kgm/sec
12.5 kgm/sec
15 kgm/sec
5 min
6 min
5 min
6 min
5 min
6 min
5 min
6 min

figure 1

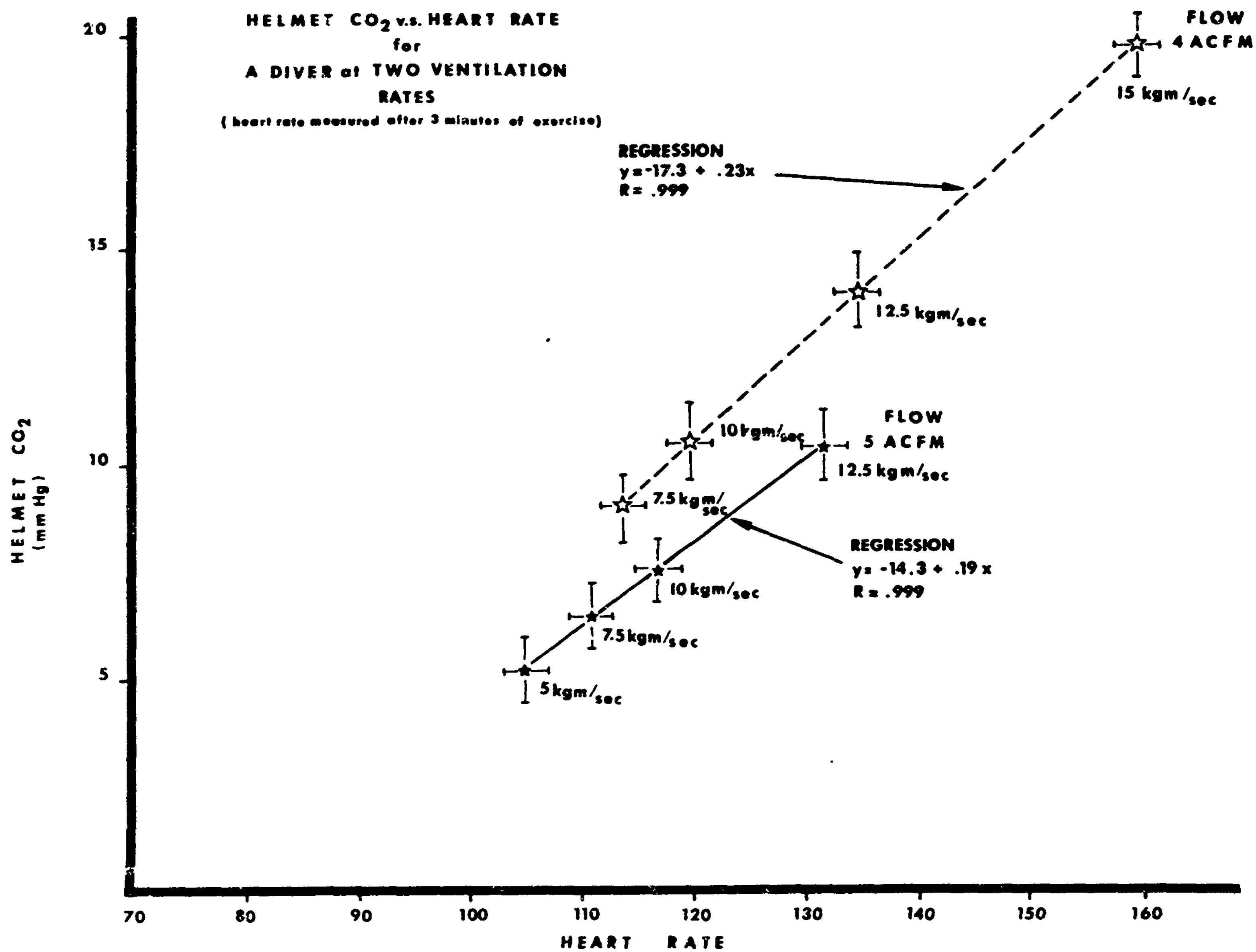
HELMET CO_2 v.s. HEART RATE
for
A DIVER at TWO VENTILATION
RATES
(heart rate measured after 3 minutes of exercise)
FLOW
4 ACFM
15 kgm/sec
REGRESSION
y = -17.3 + .23x
R = .999
12.5 kgm/sec
10 kgm/sec
7.5 kgm/sec
FLOW
5 ACFM
12.5 kgm/sec
REGRESSION
y = -14.3 + .19 x
R = .999
10 kgm/sec
7.5 kgm/sec
5 kgm/sec
HELMET CO_2
(mm Hg)
20
15
10
5
70
80
90
100
110
120
130
140
150
160
HEART RATE

figure 2

TABLE 1

HELMET FLOW RATE	OVERBOTTOM PRESSURE AT 100'	
Air Control Valve Open Full	Mark V	Mark 12 Prototype
2.4 ACFM	- - -	50 psi
4 ACFM	15 psi	110 psi
5 ACFM	- - -	125 psi
9 ACFM	50 psi	- - -

4. DISCUSSION

The mathematical model for helmet ventilation is derived in Appendix A. According to this model, if the supply gas CO_2 concentration is zero, the fraction of carbon dioxide in the helmet at any time after the diver has been at work for 3 minutes is:

$$F_{H_{CO_2}} = \frac{\dot{V}_{CO_2(ATPD)}}{\dot{V}_{Helmet}}$$

$F_{H_{CO_2}}$ = Fractional CO_2 concentration in the helmet.

$\dot{V}_{CO_2}$ = CO_2 production in liters/min. (ATPD)

$\dot{V}_{Helmet}$ = Helmet ventilation rate in liters/min. measured at depth.

ATPD = Actual temperature (21°C), pressure, dry.

$\dot{V}_{CO_2}$ is usually expressed in liters/min. STPD (Standard Temperature [0°C], pressure [760 mm Hg], dry) and the CO_2 level of the helmet is more

conveniently expressed in millimeters of mercury rather than fractional concentration. The helmet ventilation rates are expressed in ACFM (actual cubic feet per minute).

The following conversions apply:

$$\dot{V}_{CO_2} = \frac{\dot{V}_{CO_2(STPD)}}{P_B} \times \frac{294°K}{273°K} \times (760 \text{ mm Hg})$$

$$F_{H_{CO_2}} = \frac{P_{CO_2}}{P_B}$$

$$\dot{V}_{Helmet} = \text{Flow} \times 28.32 \frac{\text{L/min.}}{\text{Cubic feet/min.}}$$

where P_B is the pressure at depth in mm Hg

By making these conversions, the equation for helmet ventilation becomes:

$$P_{CO_2} = \frac{28.90\dot{V}_{CO_2(STPD)}}{\text{Flow}} \qquad (1)$$

where:

P_{CO_2} = Helmet CO_2 level in mm Hg

$\dot{V}_{CO_2}$ = CO_2 production in liters/min.

Flow = Helmet ventilation rate in ACFM

It should be noted that Flow is expressed in ACFM, or cubic feet per minute measured at depth. Flow measurements were made at the surface in terms of SCFM (surface cubic feet per minute) and were converted to ACFM by the following formula:

$$ACFM = SCFM\left(\frac{T}{P_D \cdot 294}\right)$$

where:

P_D = Absolute pressure at depth in mm Hg

T = Temperature (°K) at depth

As can be seen from equation 1, for a given helmet ventilation rate, P_{CO_2} is directly proportional to $\dot{V}_{CO_2}$. Furthermore, $\dot{V}_{CO_2}$ is related to heart rate for a given individual in the following way:

$$\dot{V}_{CO_2} = K_0 + K_1 \text{ Heart Rate}$$

where K_0 and K_1 are constants which are unique to each individual. Substituting for $\dot{V}_{CO_2}$ in equation 1:

$$P_{CO_2} = \frac{28.90K_0}{Flow} + \frac{28.90K_1}{Flow} \text{ Heart Rate} \qquad (2)$$

Notice that in equation 2 there is no expression for the actual work load. Since the heart rate is linearly related to CO_2 production, a given heart rate reflects the same CO_2 production in a given individual. Thus, the actual mechanical work being done to maintain that heart rate is immaterial. Thus, by comparing heart rate to helmet CO_2, exercise runs done at different work loads are directly comparable for the same individual.

If equation 2 is plotted with P_{CO_2} on the Y axis and heart rate on the X axis, a straight line is obtained with a slope of:

$$\frac{28.90K_1}{Flow}$$

Now if two runs are made, one at $Flow_1$, and another at $Flow_2$, the resulting slopes are:

$$\text{Slope 1} = \frac{28.90K_1}{Flow_1}$$

$$\text{Slope 2} = \frac{28.90K_1}{Flow_2}$$

Since the same individual is used in both dives, the constant K_1 is the same in both cases. Dividing the two slopes, one obtains the ratio:

$$\frac{\text{Slope 1}}{\text{Slope 2}} = \frac{Flow_2}{Flow_1} \qquad (3)$$

Referring to figure 2, a plot of heart rate vs. helmet CO_2 is indeed a straight line. From equation 3, the ratio of the slopes should be:

$$\frac{\text{Slope (4 ACFM)}}{\text{Slope (5 ACFM)}} = \frac{\text{5 ACFM}}{\text{4 ACFM}} = 1.25$$

The slopes of the two lines are .23 for the 4 ACFM line and .19 for the 5 ACFM line. The ratio of these slopes is:

$$\frac{\text{Slope (4 ACFM)}}{\text{Slope (5 ACFM)}} = \frac{.23}{.19} = 1.21$$

The experimentally determined value is very close to the predicted value of 1.25 and well within the limits of error of the experiment. Thus, the mathematical model very closely approximates the conditions of this experiment.

Using equation 1, the helmet CO_2 levels for a given CO_2 production rate at two different helmet ventilation rates are:

$$P_{CO_{2_1}} = \frac{28.90\dot{V}_{CO_2}}{\text{Flow}_1}$$

$$P_{CO_{2_2}} = \frac{28.90\dot{V}_{CO_2}}{\text{Flow}_2}$$

For a given $\dot{V}_{CO_2}$, the ratio of the helmet CO_2 levels at the two flow rates is given by:

$$\frac{P_{CO_{2_1}}}{P_{CO_{2_2}}} = \frac{\text{Flow}_2}{\text{Flow}_1} \tag{4}$$

Notice the similarity of equation 4 to equation 3. As can be seen, the ratio of slopes for helmet CO_2 levels vs. heart rate plots is not only inversely proportional to the flow rates but is directly proportional to the helmet CO_2 levels at a given heart rate (i.e. a given CO_2 production). In practice, it is not necessary to plot CO_2 level vs. heart rate since equation 4 allows direct calculation of the helmet CO_2 level at one flow rate from the measured helmet CO_2 level at a different flow rate. This relationship will probably hold only for flow rate changes of a cubic foot per minute or so since with large changes in flow rate, changes in flow patterns may cause incomplete mixing or streaming. If, however, measurements made at a low flow rate are extrapolated to predict CO_2 levels at high flow rates, equation 3 will give a value equal to or greater than the actual CO_2 level in the helmet. This is because at higher flow rates, gas moving across the diver's face will trap exhaled CO_2 and exhaust it before it has a chance to mix completely with helmet air. As can be seen from figure 2, however, a change in flow from 4 ACFM to 5 ACFM probably caused no significant change in flow pattern through the helmet.

Knowing that helmet CO_2 levels measured at one flow rate can be used to predict levels at higher flow rates, it becomes a matter of determining what helmet CO_2 levels are acceptable. The acute and chronic effects of increased inspired CO_2 have been the subject of much investigation. Unfortunately, most of this work has been done at one atmosphere under conditions which are not likely to be encountered by a diver working at depth. Extrapolating surface studies to conditions experienced at depth must be done cautiously to say the least.

The effects of increased inspired CO_2 are many, and the increased ventilation rate, increased heart rate, lowered blood pH, and the general feeling of discomfort encountered in working while breathing increased levels of CO_2 works only to the diver's detriment. Increased inspired CO_2 is associated with increased incidence of bends and in mixed gas diving with an increased incidence of oxygen toxicity symptoms. Working in a diving rig in which the CO_2 is elevated produces feeling of air hunger and discomfort. In some cases, elevated CO_2 may produce intense anxiety which inhibits the diver's ability to work and may even compromise his safety.

Based on the known effects of increased inspired CO_2, the ideal level would be that of normal air, that is a CO_2 level of less than .3 mm Hg. This of course is unobtainable without prohibitively large ventilation rates. From exercise studies done at the Navy Experimental Diving Unit over the past several years, a helmet CO_2 level of 2% seems to be the maximum that can be tolerated without subjective feelings of discomfort under normal working conditions. Even this level may prove too high under conditions of heavy exercise at depths where increased gas density impedes the divers ability to adequately eliminate CO_2 from his blood stream. Although divers are able to sustain heavy exercise levels for several minutes under these conditions, their condition following exercise is such that they require several minutes of complete rest before they are able to continue doing even very light work.

Using 2% as the maximum acceptable helmet CO_2 level, it can be seen from figure 1 that at the 12.5 Kgm/sec and the 15 Kgm/sec ergometer

settings, the helmet level went above 2%. The helmet ventilation rate in this case was 4 ACFM. The maximum helmet level at the highest work rate was about 21 mm Hg.

Referring to equation 4, the helmet ventilation rate required to bring this 21 mm Hg CO_2 level to 15 mm Hg is:

$$Flow_2 = 4 \text{ ACFM} \frac{21 \text{ mm Hg}}{15 \text{ mm Hg}} = 5.6 \text{ ACFM} \tag{5}$$

Thus, a ventilation of at least 5.6 ACFM would be required to keep the helmet CO_2 below 2% under the conditions of this experiment.

It is also useful to calculate the CO_2 production ($\dot{V}_{CO_2}$) required to raise the helmet to 21 mm Hg with a helmet ventilation rate of 4 ACFM. Equation 1 gives:

$$\dot{V}_{CO_2} = \frac{(21 \text{ mm Hg})\ (4 \text{ ACFM})}{28.90} = 2.90 \text{ L/min.} \tag{6}$$

A CO_2 production of 2.90 L/min. is high and it is unlikely that a divers' CO_2 production would go above 3.0 L/min., under most circumstances.

Using 15 mm Hg as the maximum helmet CO_2 level and 3 L/min. as the CO_2 production, equation 1 gives the helmet flow rate as:

$$Flow = \frac{28.90\ (3.0)}{15} = 5.78 \text{ ACFM} \tag{7}$$

The helmet ventilation rate calculated above differs from that calculated in equation 5 by .18 ACFM. This difference arises from the

fact that the value calculated in 5 was based on the conditions of this study while the value calculated in 7 is based on a maximum CO_2 production which should apply in almost all cases.

Rounding off the value obtained in equation 7 to the nearest ACFM, a minimum helmet ventilation rate of 6 ACFM is obtained.

By assuring that the apparatus is capable of supplying at least 6 ACFM of gas under all circumstances, one can be fairly certain that the inspired CO_2 will never exceed 2%.

The currently accepted helmet ventilation rate which appears in the 1970 U.S. Navy Diving Manual is 4.5 ACFM for each diver. This rate permits a maximum CO_2 production of about 2.3 L/min. while maintaining a helmet CO_2 level of 2%. This study shows that divers are capable of higher CO_2 productions for sustained periods. During the heaviest work load setting (15 Kgm/sec), the helmet CO_2 reached its peak in 2 minutes and maintained this maximum throughout the remaining 4 minutes of the exercise period. For most diving jobs, CO_2 production would probably be below 2.0 L/min. and a 4.5 ACFM flow rate would be more than adequate. In emergency situations, or during short periods of maximum effort, the CO_2 production might well be 3.0 L/min., and a 4.5 ACFM ventilation rate, the helmet CO_2 level would rise above 2% which would only work to the diver's detriment and could mean the difference between success and failure.

The MK-5 "Hard Hat" has been around for many years and has proved itself under the most difficult of conditions. The standard operating procedure for a 100' air dive using the MK-5 is to set the overbottom

pressure at the air manifold to 50 psi. Referring to Table 1, it can be seen that the MK-5 air control valve is capable of supplying 9 ACFM of air to the diver through 200 feet of diving hose. Thus, at this overbottom pressure, the MK-5 is capable of supplying 50% more air than the diver needs. This large reserve capacity is what has made the MK-5 such a dependable apparatus.

In contrast, the MK-12 prototype did not supply adequate amounts of gas at 50 psi overbottom. At 125 psi overbottom, the supply is barely adequate and there is no reserve capacity. Experience with the MK-12 in open sea diving has been that at 125 psi overbottom pressure, no difficulties have been noted in performing the assigned work tasks. This is because the tasks did not involve strenuous exercise and could be performed at a CO_2 production of less than 2.5 L/min. and the helmet ventilation rate was sufficient to keep the CO_2 level below 2%. In an emergency situation, or with a sustained period of heavy exercise, the MK-12 would be incapable of supplying sufficient air to keep the helmet CO_2 low which might well compromise the divers' safety.

The large differences in helmet ventilation rates at the same overbottom pressure points up the inadequacy of using overbottom pressure as the determinant of the divers' air supply. The only accurate means of determining a diver's helmet ventilation is with a flowmeter in the line. The only alternative is to determine the overbottom pressures necessary to maintain adequate helmet ventilation for each diving apparatus taking into account the various line losses due to different hose lengths. Of the two alternatives, the former is the more desirable.

Establishing a minimum helmet ventilation rate does not imply that this should be the flow to the helmet all the time. The diver regulates the helmet ventilation rate with his air control valve and might adjust it for a flow of 4.5 ACFM for a particular job. This minimum helmet ventilation rate should be interpreted to mean that if at any time the diver opens his air control valve all the way, he should obtain a helmet ventilation of 6 ACFM or greater.

It should be noted that equation 1 assumes that the CO_2 concentration in the supply air is 0%. U.S. Navy air quality standards require divers' compressed air to have a CO_2 concentration of no more than 0.05% and is air of this purity is used, equation 1 can be used to predict the required flow rates to keep the CO_2 below 2% as it was in this paper. However, if the CO_2 in the air supply is greater than .1%, equation 1 must be modified to the following form:

$$P_{CO_{2_H}} - P_{CO_{2_S}} = \frac{28.90\dot{V}_{CO_2(STPD)}}{\text{Flow}} \tag{8}$$

$P_{CO_{2_H}}$ = Helmet CO_2 level in mm Hg

$P_{CO_{2_S}}$ = Air supply CO_2 level in mm Hg

The minimum helmet ventilation as calculated in equation 7 would have to be increased according to the following formula:

$$\dot{V}_{\text{Helmet minimum}} = 6\left(\frac{P_{CO_{2_H}}}{P_{CO_{2_H}} - P_{CO_{2_S}}}\right)\text{ACFM} \tag{9}$$

4. CONCLUSIONS

(1) Helmet CO_2 level is directly proportional to CO_2 production and inversely proportional to helmet ventilation rate after 3 minutes of exercise.

(2) By measuring the helmet CO_2 level at one ventilation rate, the helmet CO_2 at another ventilation rate can be predicted by the formula:

$$\frac{P_{CO_{2_1}}}{P_{CO_{2_2}}} = \frac{Flow_2}{Flow_1}$$

(3) A CO_2 production of 3.0 L/min. is probably the maximum that would be encountered in practically all diving situations.

(4) The currently accepted ventilation rate of 4.5 ACFM per diver is inadequate to keep helmet CO_2 levels below 2% during emergency situations or during short periods of maximum work load.

(5) A helmet ventilation rate of at least 6 ACFM would insure that helmet CO_2 would remain below 2% in practically all situations.

(6) Direct flow measurements should replace overbottom pressure as the determinant of the helmet ventilation rate in operational diving.

(7) For calculating minimum helmet ventilation rates where the CO_2 level of the supply air is greater than 1 mm Hg (.1%), equation 9 should be used.

5. RECOMMENDATIONS

(1) Hard Hat systems should be designed to keep the helmet CO_2 level below 15 mm Hg (2%) with a CO_2 production of 3.0 L/min.

(2) The minimum available air supply for each diver should be established as 6 ACFM.

(3) Direct flow measurements should supplant overbottom pressure as the means of determining helmet ventilation rate.

APPENDIX A

The derivation of a mathematical model for helmet ventilation applies to any situation in which CO_2 is generated in a confined ventilated space. The general situation will be treated first then the specific conditions of this experiment will be applied to get the model in its final form.

For any closed, ventilated space, the rate at which CO_2 accumulates within that space, assuming perfect mixing, is the difference between the amount being removed and the amount being added. Mathematically this is expressed as:

$$V_H(dF/dT) = \dot{V}_{CO_2}(ATPD) + F_S\dot{V}_{HS} - F\dot{V}_{HE}$$

V_H = closed space volume (liters)

dF/dT = change in CO_2 fraction with time

T = Time (min)

$\dot{V}_{CO_2}$ = CO_2 production (L/min) (1)

F_S = Fraction of CO_2 in supply gas

F = Fraction of CO_2 in the closed space

$\dot{V}_{HS}$ = Ventilation supply rate (actual L/min)

$\dot{V}_{HE}$ = Ventilation exhaust rate (actual L/min)

Equation 1 assumes complete mixing.

Rearranging equation 1 and solving for dF/dT:

$$\frac{dF}{dT} = \frac{1}{V_H}\dot{V}_{CO_2} + \frac{F_S \dot{V}_{HS}}{V_H} - \frac{F\dot{V}_{HE}}{V_H} \qquad (2)$$

As written, equation 2 contains three variables; $\dot{V}_{CO_2}$, F, and $\dot{V}_{HE}$. All other terms are assumed constant. In open circuit helmet diving, $\dot{V}_{HE}$ will be very close to $\dot{V}_{HS}$. In this study, the differential pressure from the inside to the outside of the helmet did not change significantly with respiration indicating a constant helmet exhaust rate throughout the respiratory cycle. For neck seal helmets and full face masks, $\dot{V}_{HE}$ is time dependent decreasing during inspiration and increasing during expiration. In situations such as these assuming a constant $\dot{V}_{HE}$ will overestimate the CO_2 level within the mask or helmet. Confining the derivation to s uations in which $\dot{V}_{HE}$ is constant and equal to $\dot{V}_{HS}$ equation 2 can be written as:

$$\frac{dF}{dT} = A_1\dot{V}_{CO_2} - A_2F + A_3 \qquad (3)$$

where

$$A_1 = 1/V_H$$

$$A_2 = \dot{V}_{HE}/V_H$$

$$A_3 = F_S \dot{V}_{HS}/V_H$$

Rearranging equation 3:

$$\frac{dF}{dT} + A_2 F - A_3 = A_1 \dot{V}_{CO_2} \qquad (4)$$

The above is a linear differential equation which has an integrating factor of $e^{A_2 T}$. Multiplying 4 through by the integrating factor:

$$e^{A_2 T}\frac{dF}{dT} + A_2 F e^{A_2 T} - A_3 e^{A_2 T} = A_1 e^{A_2 T} \dot{V}_{CO_2}$$

Integrating both sides gives:

$$e^{A_2 T} \left(F - \frac{A_3}{A_2}\right) = A_1 \int e^{A_2 T} \dot{V}_{CO_2} + B$$

where B is a constant of integration. Since $\dot{V}_{HE} = \dot{V}_{HS}$ the ratio A_3/A_2 is equal to F_S and the above equation reduces to:

$$e^{A_2 T} (F - F_S) = A_1 \int e^{A_2 T} \dot{V}_{CO_2} + B \qquad (5)$$

Equation 5 is the general form of the expression for helmet CO_2 fraction assuming complete mixing. If the subject is at equilibrium, that is $\dot{V}_{CO_2}$ is constant, then the solution for equation 5 is:

$$e^{A_2 T}(F - F_S) = \frac{A_1}{A_2} e^{A_2 T} \dot{V}_{CO_2} + B \tag{6}$$

Dividing by $e^{A_2 T}$

$$(F - F_S) = \frac{A_1}{A_2} \dot{V}_{CO_2} + Be^{-A_2 T} \tag{7}$$

At time $T = \emptyset$

$$F = F_{rest} \text{ and } \dot{V}_{CO_2} = \dot{V}_{CO_2 rest}$$

so that

$$(F_{rest} - F_S) = \frac{A_1}{A_2} \dot{V}_{CO_2 rest} + B$$

solving for B

$$B = (F_{rest} - F_S) - \frac{A_1}{A_2} \dot{V}_{CO_2 rest}$$

If the subject is at rest for several minutes before beginning work, the resting CO_2 fraction is also given by equation 7.

From equation 3

$$A_2 = \dot{V}_{HE}/V_H$$

The helmet volume is approximately .4 ft^3 and $\dot{V}_{HE}$ is at least 4.0 ACFM thus;

$$A_2 \geq 10$$

Using this value for A_2 it can be seen that the exponential term in 7 will become vanishingly small after only 2 or 3 minutes; thus the resting helmet CO_2 fraction is

$$(F_{rest} - F_S) = \frac{A_1}{A_2} \dot{V}_{CO_2 rest}$$

Looking back at the expression obtained for B, it is obvious that B = Ø. Thus, for a steady $\dot{V}_{CO_2}$ the helmet fraction is given by

$$(F - F_S) = \frac{A_1}{A_2} \dot{V}_{CO_2} \qquad (8)$$

Equation 8 assumes that equilibrium has been reached and that $\dot{V}_{CO_2}$ is constant.

In the present study, the helmet CO_2 concentration leveled off after 2-3 minutes and all measurements were made after

3 minutes to insure equilibrium conditions were present. For most situations, including this experiment, the CO_2 concentration in the supply hose is so low that it can be neglected. Assuming F_S is approximately 0 and substituting for A_1 and A_2 equation 8 becomes

$$F = \frac{\dot{V}_{CO_2}}{\dot{V}_{He}} \tag{9}$$

Where

F = Fraction of CO_2 in the closed space

$\dot{V}_{CO_2}$ = CO_2 production in actual liters per minute

$\dot{V}_{HE}$ = Helmet flow rate in actual liters per minute